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COLLABORATIVE UNMANNED VEHICLES FOR MARITIME DOMAIN AWARENESS

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Unmanned vehicles are becoming a critical component of military operations. As the vehicles develop in capability, there will be a trend for heterogeneous classes of unmanned vehicles to be able to work in a more collaborative fashion. This paper discusses the research initiatives by the Naval Postgraduate School Center for Autonomous Unmanned Vehicle Research for achieving greater effectiveness in naval operations through collaborative behavior. It focuses on three separate initiatives and discusses results from recent Tactical Network Topology (TNT) experiments.

1 Introduction

The utility of unmanned vehicles is unquestioned. Current US military operations at home and overseas suggest that the use of unmanned vehicles will continue to grow. As the roles and sophistication of unmanned vehicles continue to improve the collaboration between various categories of vehicles will also continue to emerge. The reason for this is at least three-fold. First, costs for distributed unmanned vehicles large oceans areas will be less expensive than equivalent manned operations. Second, the search capability of the unmanned systems rival that of manned systems and this will continue to improve. Third, the distributed autonomous system will increase productivity by permitting personnel to place greater emphasis on achieving objectives rather than understanding the situation through information discovery.

We define a distributed autonomous system DAS as a combination of autonomous underwater (AUV), surface (USV) and aerial vehicles (UAV) and unattended ground (and underwater) sensors (UGS). The envisioned system would operate in an autonomous or semi-autonomous method since guiding operational principles would be given from personnel but to achieve the objectives the autonomous system would generate the optimal control behaviors to the individual vehicles. The system could allocate resources depending on some measure of optimality (e.g. speed, energy, cover rates, etc.).

In this paper, we describe three instances of DAS research. In the first case we describe the use of UAVs as a high bandwidth communication link between with AUVs and the Command Ship where the UAV has an autopilot controller to maintain optimal loitering behavior for maximizing the bandwidth of the communications link (Horner and

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Healey, 2004). In the second case an AUV uses ranging information from a network of underwater acoustic modems to maintain navigation accuracy while permitting the vehicle to stay underwater for longer periods of time (Hahn, 2005). It highlights the collaboration of fixed sensor nodes with unmanned vehicles and how AUVs can use existing network infrastructure for improving navigation and stealth. Finally, we discuss the development of a tactical network that brings together information from various unmanned vehicles and sensors to provide combat divers with in-stride, relevant information as they conduct military operations.

2 High Bandwidth Communications Through UAVs

For US naval operations, Shallow Water Organic Mine Countermeasures (SW-OMCM) is the process of identification and location of minefields that could potentially hold off amphibious landing. AUVs have proved to be a useful vehicle for the search and detection of mines and obstacles. In a wide area search along an extended coastline groups of AUV would be deployed en masse to determine viable routes ashore for an amphibious landing.

Rather than waiting until the vehicles return from the mission, it is desirable to have the vehicles report back at discrete times to update progress and download collected data. To do so a high bandwidth communications link is necessary between the AUV and the command ship. This link would be useful for sending back sonar, bathymetry, video, and vehicle state. As the operation continues, the distributed information can be used to appropriately re-allocate assets as necessary.

The optimal position for maximizing throughput on the wireless communications can be calculated from the intersection of the Signal to Noise Ratios (SNR) between the Command ship and the AUVs associating into the wireless network. The UAVs can use this information to generate an optimal loitering point. This loitering point is dynamic since all vehicles are assumed to be in motion and the AUVs associate into the network while on the surface but leave the network once underwater. The goal of the project is to use available signal strength information to automate the UAV navigation route. This is attractive since:

1. It improves system performance since if one AUV fails another can be re-tasked to ensure complete coverage
2. It reduces the time necessary to conduct the search and increases the speed of response. This is critical for military operations.
3. It permits greater operational flexibility because more landing sites can be quickly searched and evaluated.

The 2.4 GHz wireless radio networks were originally designed to be stationary nodes so experimentation was necessary to determine the suitability of the radios and communication protocols for mobile nodes. There were five different nodes in the network, they included:

1. Acoustic Radio Interactive Exploratory Server (ARIES) AUV (Figure 1). It was built by the Center for testing communications, underwater sensors and research into system control.
2. Tactical Ground Station (Figure 2). It includes the wireless access point, a pan and tilt, high gain, directional antenna, Laptop PC and 900 MHz Freewave radio
3. Tactical Expendable Remote Navigator (TERN) UAV (Figure 3). It has a wingspan of 11 feet and duration of approximately 2 hours with a payload of 25 lbs.
4. Balloon (Figure 4). The balloon was used when the UAV wasn't available and as a communications bridge from the ARIES to the TERN.
5. Support ship. It was used to deploy and recover ARIES. It permitted researchers to monitor to the wireless signal from the water.

Figure 1. NPS ARIES AUV

Figure 2. Tactical Ground Station

Figure 3. TERN UAV

Figure 4. Balloon

The TERN transmitted its GPS position through the Freewave radio; this enabled the ground station to track the UAV. All four nodes had the Commercial off the Shelf (COTS) Cisco 802.11b/g 2.4 GHz wireless radios. Figure 5 shows the network architecture of the system.

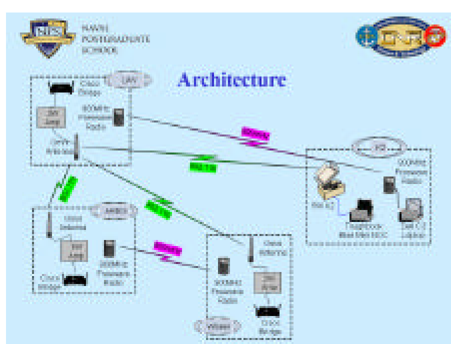


Figure 5. Network Architecture

2.1 Experimentation Results

During an NPS Tactical Network Topology experiment at Camp Roberts, CA the communication link between a surfaced AUV and the Tactical Ground Station was successfully tested to approximately 15km using TERN UAV as the communications bridge. The UAV flew at approximately 1km AGL. Several data files were transferred from the AUV at an average rate of 196kbps. In a follow-up military exercise at Camp Lejeune, NC, it was demonstrated that a range of 23km could be achieved using the Balloon as the surrogate UAV. Figure 6 shows the link quality as a function of distance from the balloon to the AUV. The second half of the communications channel, from the Balloon to the Tactical Ground Station was at a distance of 15km. The link quality was again measured by sending various sized digitized videos across the communication link.

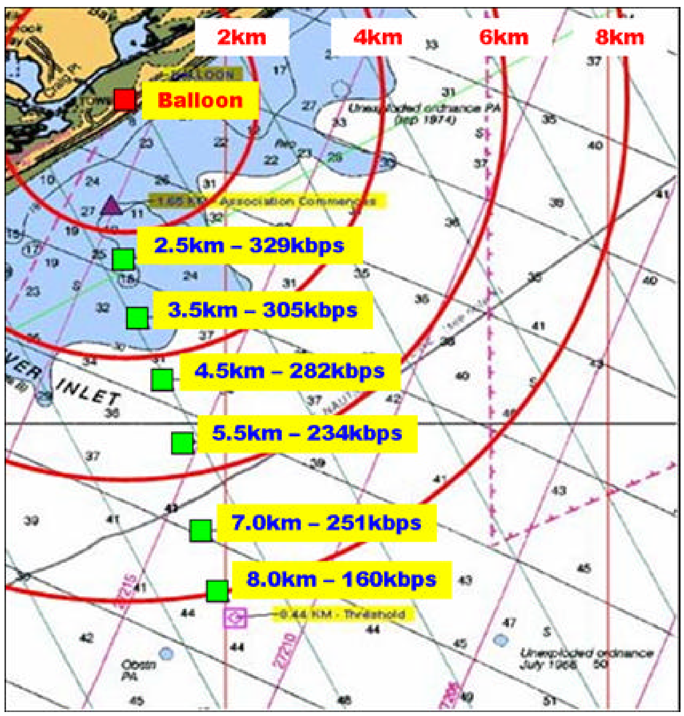


Figure 6. Transmission rates at various distances

3 Seaweb

Acoustic communications networks are a useful technology for enabling continuous, long-term environmental monitoring in the worlds' oceans. These networks allow autonomous collection of real-time oceanographic data from distributed underwater sensors. They can also be used for Command and Control (C2) of autonomous underwater vehicles (AUVs). In fact, AUVs can serve as mobile network nodes to greatly improve the effectiveness of the underwater network in several ways: 1) Mobile nodes can be repositioned to alter the network's topology, extend communications into new areas, or to maximize data transfer rates through close proximity with fixed nodes; 2) They can also serve as gateways to transfer information from undersea sensors to C2 centers via high-bandwidth radio communications; and 3) Since AUVs can move in response to changing local conditions, they can allow scientists to perform adaptive sampling of the environment. In May 2005, the NPS conducted an experiment using the ARIES AUV as a mobile node in the Seaweb network.

Seaweb is an acoustic communications network developed by the US Navy, employing deployable acoustic transducers with Benthos telesonar modems. A Seaweb network is typically comprised of a grid of repeater nodes fixed on the seafloor and a radio-acoustic communications (RACOM) gateway buoy, which provides operators with remote access to the underwater network. For this experiment, the ARIES vehicle was used as a mobile network node (Figure 7).

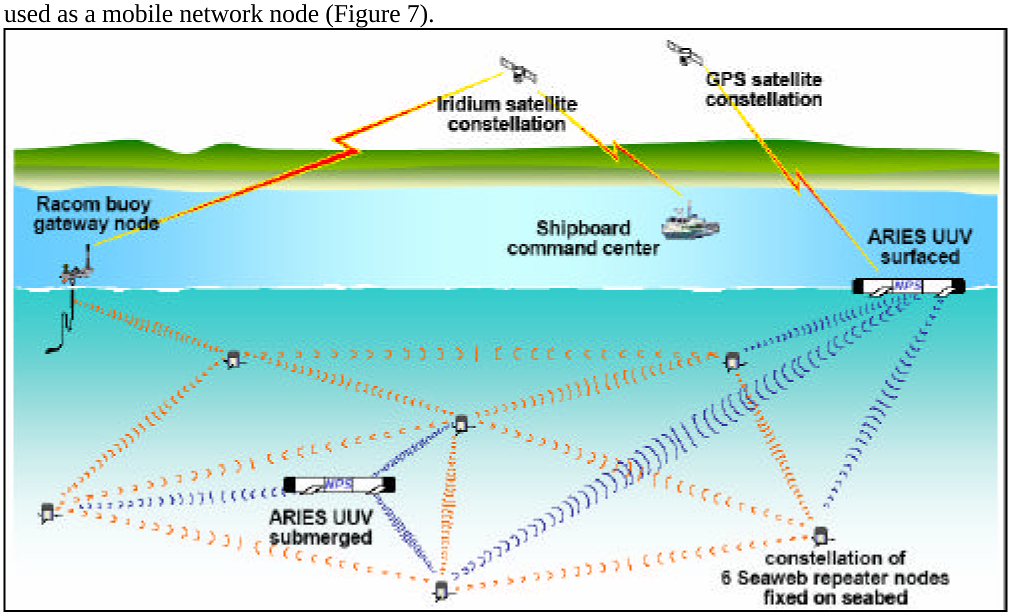


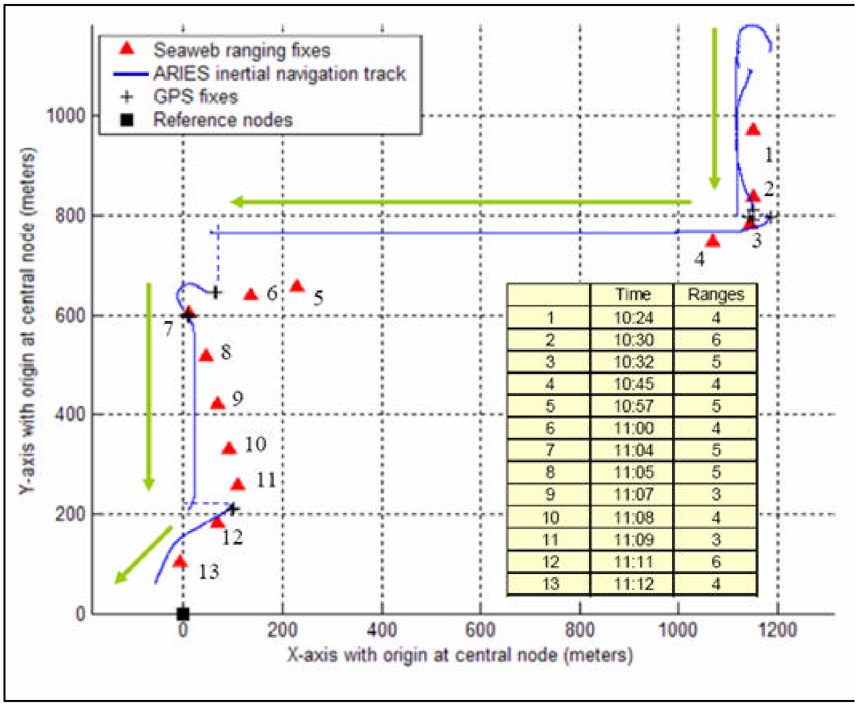
Figure 7. Seaweb Architecture with the ARIES AUV

Seaweb communications produce node-to-node ranging data as a byproduct of the link-layer protocol. The primary objective was to track the ARIES vehicle within the Seaweb network using range data generated through communications with the fixed seafloor nodes. By periodically sending broadcast pings from the ARIES acoustic modem and measuring the response times from each node, the resultant range data was used to localize the vehicle with respect to known locations for each fixed node (Hahn 2005).

This experiment produced several interesting results. In one test, operators successfully sent an "Abort" command over the network to terminate an ARIES mission. Communications were achieved at node-to-node distances of up to 2500 meters. By relaying messages through multiple nodes, these ranges can be multiplied to extend C2 ranges even further. These tests demonstrated how the Seaweb network can greatly extend C2 ranges between a command ship (or gateway buoy) and an AUV.

Perhaps most compelling was Seaweb's ability to track the ARIES vehicle while underwater. Network-produced estimates of vehicle position were more accurate than the vehicle's own inertial navigation positions (based on dead-reckoning). Figure 8 below shows an ARIES track for one mission. After the long East-to-West and North-to-South underwater (inertial navigation only) legs of its track the vehicle performs a popup maneuver to obtain a GPS fix and correct accumulated navigation errors. At each popup, the vehicle's navigation filter corrects its position estimate to the GPS position (dashed lines). In this experiment, Seaweb's ranging fixes for these legs (fixes 3 through 6 and 8 through 11, respectively) correspond more closely with the path the vehicle likely took between GPS fixes.

These results hold real promise for ongoing research at NPS. Next year, the Center for AUV Research plans to develop real-time navigation algorithms for AUVs that take advantage of Seaweb's acoustic ranging capability to provide precise underwater navigation without surfacing periodically for GPS fixes. These algorithms will be implemented on the ARIES AUV to determine the positioning accuracy of a Seaweb-based "underwater GPS" system. Another potential use for this technology would be the precise localization of fixed sea-floor nodes using GPS-equipped vehicles on the surface. A possible tactical scenario could involve an AUV that transits to an operating area in which Seaweb nodes have been deployed indiscriminately (i.e. air-dropped). When the AUV makes contact with an underwater node, it surfaces and travels through the grid to collect range data from its GPS position to each sea floor node. This data would be used to compute and store the ground truth position of each node to generate a map of the underwater "constellation" akin to the GPS satellite system. The AUV could then submerge and use acoustic ranging from these computed positions to obtain underwater navigation fixes during all future missions.



	Time	Ranges
1	10:24	4
2	10:30	6
3	10:32	5
4	10:45	4
5	10:57	5
6	11:00	4
7	11:04	5
8	11:05	5
9	11:07	3
10	11:08	4
11	11:09	3
12	11:11	6
13	11:12	4

Figure 8. ARIES Navigation with Seaweb Ranging Fixes

4 Tactical Network Topology Experimentation

A large scale deployment of distributed unmanned systems and sensors makes the development of a collection, processing and re-distribution network equally important. A third goal of on going work at NPS is the distribution of relevant information back to all levels of command. On the tactical level, this means tasking unmanned vehicles to reconnoiter areas in advance of arriving forces and distilling the results of the surveillance into key elements. For the last three years, there have been a series of quarterly experiments now called the Tactical Network Topology (TNT). The goal of the experiments has been to create a laboratory for bringing together students and faculty for testing new concepts for tactical networks and autonomy with unmanned vehicles. It is within the context of these experiments that the Center has developed a nascent capability for providing maritime situation awareness for combat divers.

The key additional component to the mix of networked unmanned systems is the NavBoard handheld dive board (Figure 9). The NavBoard has a molded dive board housing a waterproofed unit and dead reckoning mechanism. It is a rugged hand-held computer capable of receiving Global Positioning System (GPS) data and displaying networked information. It permits swimmers to obtain a GPS fix on the surface and navigate underwater using programmed waypoints and dead reckoning. It also houses an 802.11b antenna and PCMCIA card in order to communicate with the wireless network.

Figure 9 – NavBoard displaying a sonar image received over the TNT network

Figure 10 shows the network topology deployed in Monterey Bay. The goal of the experiment was to collect unmanned vehicle sensory information and have the combat diver access the information from the network to affect ingress routes ashore. In the experiment, the ARIES collected Forward Looking Sonar (FLS) to ensure the littoral area was clear of mines. After completion of the mission, ARIES surfaced and transmitted FLS images using a WLAN link to a support ship. The support ship forwarded the images into the land-based network via an 802.16 5.0 GHz Orthogonal Frequency Division Multiplexing (OFDM) wireless communication link. This information was automatically available to diver team. Next the NPGS Pelican UAV collected and transmitted digitized video into the network. The video camera scanned the site where the team planned to go ashore. Once in the network, the dive team downloaded the video, while on the ocean surface conducting a GPS navigation fix.

The Pelican, Figure 11, is a research aircraft operated by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS). It can function as either a standalone, manned sensor platform or—with the installation of the Predator Avionics Module and associated Ground Station—as a manned Predator UAV surrogate. The aircraft is a highly modified Cessna 337/O-2A Skymaster twin-engine airframe from which the forward engine has been removed. It can travel at speeds from 80 – 130 knots, and fly in FAA airspace allowing experimentation with networks without being restricted to Military airspace.

Originally developed for optionally-piloted, long-endurance, low-altitude atmospheric and oceanographic research, the Pelican has a large payload capacity (350 lb. in nose, more in cabin or on wing hardpoints) and supports several diverse payloads (1.2 kW available power). The payload for these TNT experiments included an 802.16 wireless bridge, pan-tilt-zoom (PTZ) camera system, and Pelco remote video monitoring software to share the Pelican's aerial surveillance data with other network nodes in near real time. The Pelican also carries an 802.16 (OFDM) system link.

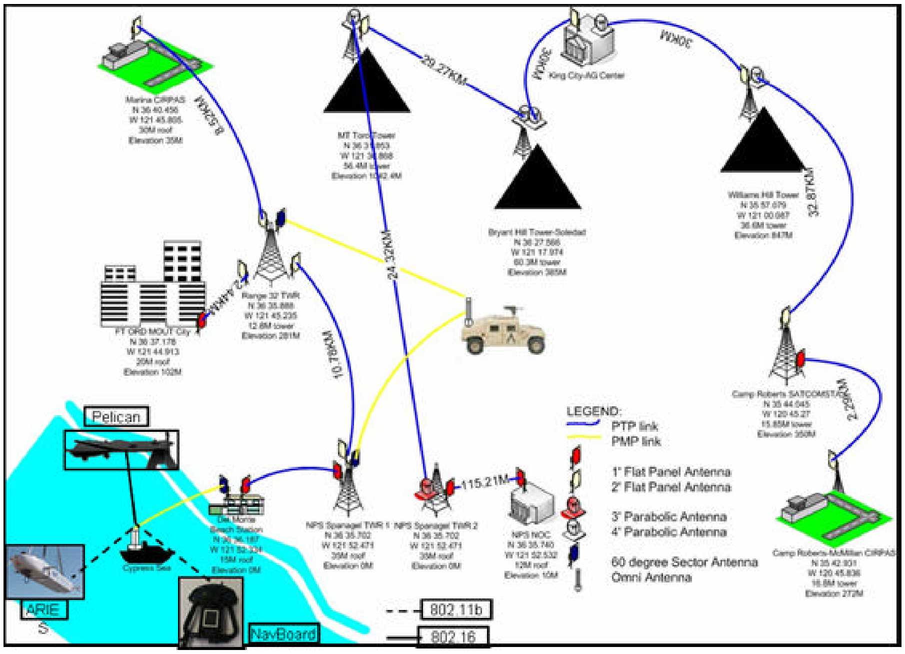


Figure 10. TNT Network Architecture for Monterey Bay Experimentation

Figure 11 – Pelican In Flight

Figure 12 – D/V Cypress Sea

The D/V Cypress Sea is a 40-foot aluminum workboat reconfigured for recreational dive charters (Figure 12). Cypress Sea is regularly chartered by the NPS Center for AUV Research for use as a mobile command vessel during ARIES operations. It has a stern hoist capable of launching and recovering ARIES, and ample cabin space for several computer workstations. For these TNT experiments, an omni-directional OFDM antenna was installed on the mast of the Cypress Sea. Several laptops comprising a local area network (LAN) were connected to the Pelican and the NOC via an 802.16 bridge and the OFDM antenna. This allowed Cypress Sea to function as a "mobile NOC" for ARIES and the NavBoard, which communicated with the 802.16 network using an 802.11b link to the LAN. The laptops on the Cypress Sea also provided real time displays of Pelican aerial surveillance data, overall network status, and the Situational Awareness Multi Agent System (Figure 13).

Test Objectives

The overall objectives for the TNT 05-2 experiment were to evaluate the NavBoard's navigational performance as well as demonstrate and evaluate above - and below-water SA provided to submerged combat swimmers, while considering real time meteorological and oceanographic (METOC) effects on SA. These objectives had three initial components:

1) Determine the navigation accuracy of the existing NavBoard.
2) Examine alternatives for improving the navigation accuracy.
3) Explore the use of the /TNT wireless network architecture and SA application for providing above - and below-water SA to submerged swimmers.

Measures of Performance

Measures of system capability and performance for were defined as follows:

- NavBoard navigation accuracy as function of path length and direction relative to current
- Ability to update submerged swimmer waypoints through the network,
- Ability (Data rates, Ranges) to provide above- and below-water SA to the submerged NavBoard using combination of 802.11b and 802.16/OFDM
- Ability of ARIES ground control station to display navigation path while underway
- Ability of ARIES AUV to locate and ID/image mines in shallow water using forward looking sonar and an automated search pattern
- Initial human systems integration data for NavBoard from combat swimmers
- Ability of current models to predict real time radar threat assessment for rigid hull inflatable boat (RHIB)
- Accuracy of current models to predict real time effects of local METOC conditions on electro-optical (EO) "visibility" of onshore objects from ship

Figure 13 – LAN onboard Cypress Sea

Results

During the course of the exercise, we

- Established and verified 802.16 link connectivity between Cypress Sea and NPS NOC and between Pelican and NPS NOC. Established and verified 802.11b link connectivity between ARIES and 802.11b bridge equipment onboard Cypress Sea, and between Cypress Sea networking equipment and NavBoard.

- Successfully transferred previously gathered and recorded sonar images of mines stored in ARIES to a laptop computer via 802.11b bridge onboard Cypress Sea, and then from laptop to NPS NOC file system using Microsoft “Groove” file sharing software.

- Obtained updated waypoints from a GPS receiver on Cypress Sea by maneuvering and transferred them to NPS NOC via “Groove”. Waypoints were not determined directly from NPS NOC due to time constraints in the lab. We successfully transferred updated swim waypoints from NPS NOC to NavBoard, via Cypress Sea, and updated swim waypoints were successfully retrieved by NavBoard and were readable.

Network Transmitted Waypoints:
CS1 36.61736°N / 121.87247°W
CS2 36.61470°N / 121.866897°W
CS3 36.62464°N / 121.86352°W

- Successfully transferred video frame images such as that shown in Figure 14 recorded by the Pelican UAV to NPS NOC to Cypress Sea to NavBoard. The Pelican video frame was successfully retrieved by NavBoard and was readable.

Figure 14 – Pelican Video Image (as seen on Cypress Sea)

- Conducted range run to determine maximum 802.16 connection distance between Cypress Sea and Beach Lab with NPS NOC monitoring Cypress Sea distance and throughput of 802.16 connection. Maximum connection distance obtained may have been limited by Sea State 3 conditions at point of network dropout.

While preliminary, these experiments successfully demonstrated several new capabilities for providing above - and below-water SA to navy swimmers through networked links. Notable accomplishments include:

1) The ARIES AUV was connected as a node on the wireless network for the first time. This enabled the AUV to share near real time information with other network nodes. Specifically, ARIES received aerial images from the Pelican aircraft and these images were viewed on another wireless network node aboard the Cypress Sea. Further development of this capability will enable AUVs to be re-tasked by modification of their run plans to avoid exclusion zones such as kelp beds identified by unmanned aerial platforms.

2) Six images of mine-like objects (MLO) obtained with the ARIES forward looking sonar (FLS) were sent to the NOC and forwarded for display on the NavBoard.

3) Near real-time images taken by the Pelican were also displayed on the NavBoard.

4) NavBoard waypoints were updated by the NOC based upon the SA awareness provided.

Capabilities 2 - 4 could enable future combat swimmers to modify their ingress/egress routes based on situational awareness provided by unmanned aerial and underwater platforms. In addition, special clearance teams could utilize improved location information and/or images of mine-like objects provided by these unmanned platforms to perform their missions more effectively.

5. Conclusion

The use of distributed autonomous systems holds great promise for improving Maritime Domain Awareness. The different classes of vehicles and sensors provide a more complete understanding of the environment and can be used together in novel ways resulting in a synergist effects. There are also many challenges to fielding this type a capability. Foremost is the logistic support necessary for maintaining vehicles in an ocean environment for long periods of time. In this paper, we have highlighted three different aspects of research regarding collaborative vehicles, UAV optimal positioning for maximizing WLAN communications, AUV geo-positioning through networked underwater acoustic modems and distribution of unmanned sensor data for tactical situation awareness. One of the remaining challenges is developing a system architecture that utilizes the network infrastructure to manage the unmanned systems so that assets are optimally allocated.

6.0 Acknowledgements

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